

Orbit Determination for the Lunar Reconnaissance Orbiter Using an Extended Kalman Filter

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- ***The Lunar Reconnaissance Orbiter (LRO) is a lunar polar-orbiting mission designed to improve knowledge of the Moon's surface, topography, and radiation environment; to search for ice; and to study permanently shadowed regions of the Moon***
- ***LRO launched on June 18, 2009***
 - Entered its nominal orbit on September 15, 2009
 - Maintained a 50-km circular orbit until December 2011
- ***In December 2011, LRO was maneuvered into an elliptical orbit of approximately 40 km x 180 km, where it has remained since then***
 - There have been some slight adjustments to the elliptical orbit for science and power reasons
- ***The Flight Dynamics Facility (FDF) at the Goddard Space Flight Center (GSFC) performs daily operational orbit determination (OD) for LRO in support of mission operations and science planning***
 - Civil servants in the GSFC Navigation and Mission Design branch perform LRO trajectory design and maneuver planning and calibration
 - The LRO Lunar Orbiter Laser Altimeter (LOLA) science team also performs OD for the purpose of high-precision orbit reconstruction and gravity field estimation

- ***Since launch, the FDF has performed daily OD for LRO using the Goddard Trajectory Determination System (GTDS)***
 - GTDS is a batch least-squares (BLS) estimator
 - The tracking data arc for OD is 36 hours
- ***Current operational OD uses 200x200 lunar gravity, solid lunar tides, solar radiation pressure (SRP) using a spherical spacecraft area model, and point mass gravity for the Earth, Sun, and Jupiter***
- ***LRO tracking data consists of range and range-rate measurements from:***
 - Universal Space Network (USN) stations in Sweden, Germany, Australia, and Hawaii
 - A NASA antenna at White Sands, New Mexico (WS1S)
 - NASA Deep Space Network (DSN) stations
 - DSN data was sparse and not included in this study
- ***Tracking is predominantly (~50%) from WS1S***
- ***The OD accuracy requirements are:***
 - Definitive ephemeris accuracy of **500 meters total position root-mean-squared (RMS)** and **18 meters radial RMS**
 - Predicted orbit accuracy less than **800 meters root sum squared (RSS)** over an **84-hour prediction span**

- ***GTDS easily met mission OD requirements when LRO was in the 50 km circular orbit***
- ***Since returning to the elliptical commissioning orbit, meeting definitive and predictive accuracy requirements has been challenging, particularly during periods of high-beta angle***
- ***In response to this, the FDF implemented a number of improvements to GTDS OD processing***
 - For more details, see “Lunar Reconnaissance Orbiter Orbit Determination Accuracy Analysis” from the 24th ISSFD (Laurel, MD, 5 - 9 May 2014)
 - Prediction accuracy during high-beta season remains an issue because of coarse spacecraft area modeling
- ***A Kalman filter has some natural advantages over GTDS BLS for LRO OD***
 - Improved (shorter) processing time
 - Potentially improved definitive OD accuracy
 - A potentially realistic, time-dependent estimate of orbit uncertainty
 - With the Orbit Determination Tool Kit (ODTK), a more capable area model for prediction

- ***ODTK is a commercially-available Extended Kalman Filter (EKF)***
 - Developed and maintained by Analytical Graphics, Inc.
 - ODTK implements an EKF and fixed-interval smoother, and native utilities for graphing and analyzing solution data
 - ODTK implements high-fidelity force modeling and supports over 150 measurement types
- ***Process noise, rather than simply generalized, is tied to physical models of dynamic effects***
 - Gravity model process noise is derived from the lunar gravity model, incorporating errors of omission (truncation) and commission (formal model error)
 - SRP process noise, along the Sun direction and off-axis noise scaled by the magnitude of SRP, may be added to accommodate coarse spacecraft area modeling
 - Generalized (not physically-connected) process noise may also be added

- ***The time span of March 11 to July 13, 2013 was chosen for analysis***
 - Same time span used in the prior analysis reported at ISSFD 2014
 - Period spans low to high beta angles and includes a full-Sun orbit period, five momentum unloads, and one station-keeping maneuver
 - GTDS OD, using an updated gravity model, experienced 14 failures of the 800-meter predicted accuracy requirement over this time span
- ***ODTK was configured to run in an automated fashion similar to how it would be used in an operational scenario***
 - After initialization, the data was filtered in 1-day spans, from 12:00 to 12:00 UTC
 - A 5-day predicted ephemeris was generated from the daily final estimated filter state
 - The smoother then ran backwards for a total of 4 days, generating a smoothed definitive ephemeris
 - For each analysis series, graphs of scaled residuals, covariance, estimated parameters, and filter-smoother consistency were generated
 - Additional scripts performed comparisons between the ODTK solutions and precision OD ephemerides produced by the LOLA team

- ***The performance of each tuning scenario was evaluated primarily on definitive and predictive accuracy versus mission requirements***
- ***All cases yielded definitive accuracy better than requirements, and definitive accuracy was consistent for all tunings considered***
 - It is likely that a filter will give good definitive accuracy for a satellite with dense tracking like LRO
- ***As a result, predictive accuracy was the most important evaluation criteria***
 - In particular, how many times the each tuning scenario exceeded the 800-meter, 84-hour prediction accuracy requirement
- ***In addition to definitive and predictive accuracy, filter performance was also evaluated based on analysis of the time history of any estimated parameters, scaled residuals, filter covariances, and filter-smoother consistency***

$$R(t) \approx \frac{\hat{X}_{filter}(t) - \hat{X}_{smoother}(t)}{\hat{\sigma}_{filter}(t) - \hat{\sigma}_{smoother}(t)}$$

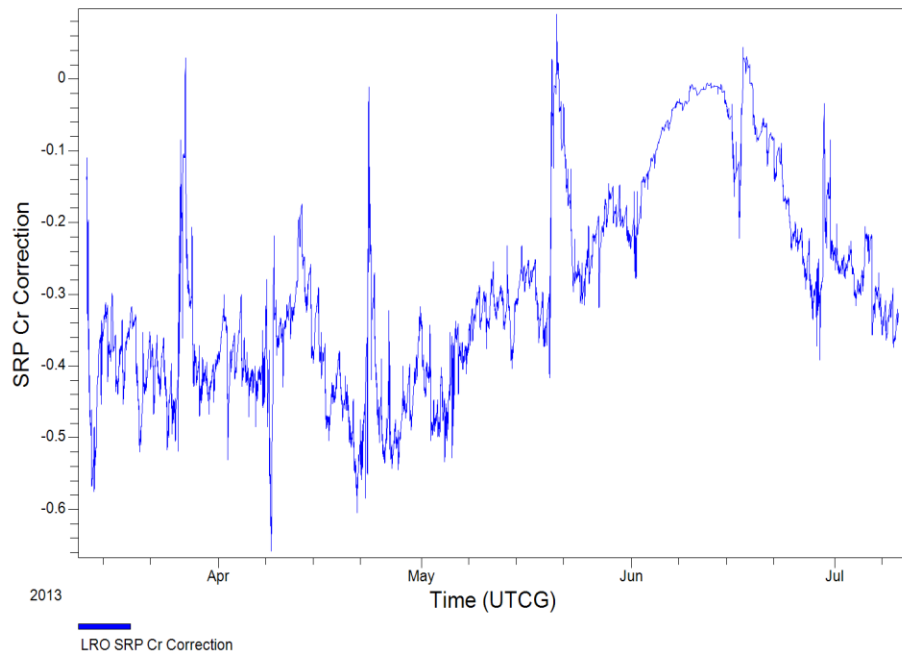
- ***The McReynolds' filter-smoother consistency test computes a unitless metric at each point of overlap between the filter and smoother that is the ratio of the difference between the filter and smoother state estimates to the difference in filter and smoother formal covariance***
- ***Gross satisfaction of the filter-smoother consistency test is a condition for optimal OD (Wright)***
 - Filter and smoother covariance cannot be presumed “realistic” if not consistent
 - Persistent excesses of the test metric are an indication of stress on the filter and a sign that some observable effect is ignored, mis-modeled, or poorly tuned
- ***The test may be applied to any estimated parameter, including SRP correction***

- ***The GRAIL GL0660B model was chosen***
 - JPL-derived gravity model at maximum degree and order 660
- ***Three truncations were evaluated: 100x100, 150x150, 200x200***
 - The 100x100 case was poor
 - 150x150 and 200x200 performed similarly, with 200x200 being slightly better
- ***The 200x200 truncation was selected***
 - Filter-smoother run time for the 200x200 case was less than 10 minutes
 - A 200x200 model is in use for operational LRO OD with GTDS

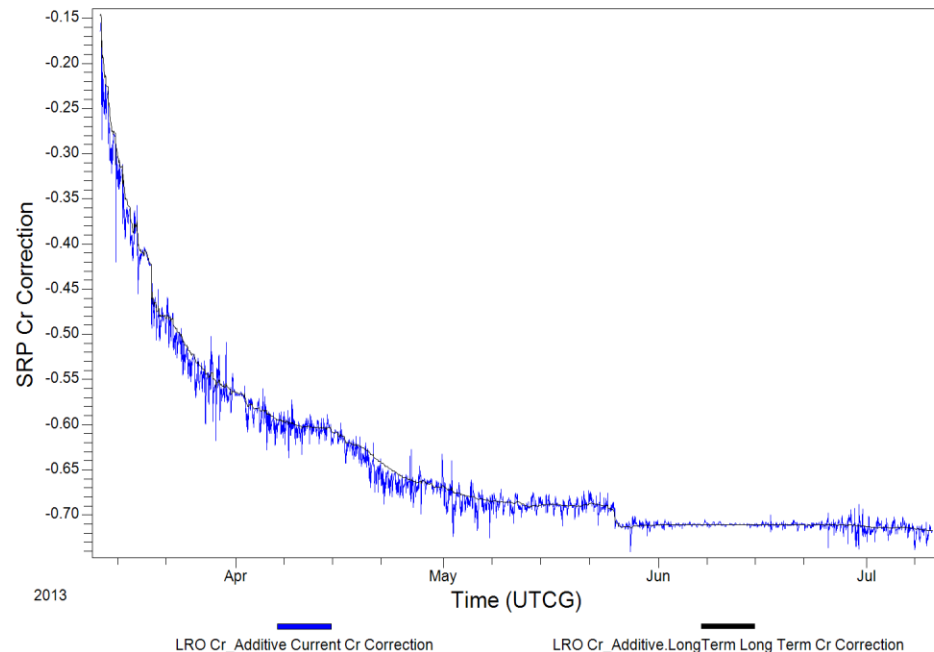
Truncation	Definitive RMS Total Position Accuracy (Meters)	Number of 84-hour Predictions in Excess of 800 Meters
100 x 100	18	43
150 x 150	4	15
200 x 200	3	12

- ***A spherical area model was used***
- ***ODTK provides three stochastic models for estimating a correction to the nominal coefficient of SRP***
 - Random walk, Gauss-Markov, and Vasicek
- ***The Vasicek model acts like a superposition of a random walk and Gauss-Markov model, facilitating separation of long-term and short-term effects***
- ***The Vasicek model was found superior to the Gauss-Markov (GM) model for SRP***
 - SRP corrections using the Gauss-Markov model tended to be inconsistent across the evaluation span
 - Estimates using the Vasicek model converged to a stable long-term value with small variations about that mean value
- ***Addition of supplemental off-axis SRP process noise at the level of 30% of the nominal force of SRP was also found beneficial***
 - In principle this accounts for things like using a coarse spherical spacecraft area model

Gauss-Markov Estimation



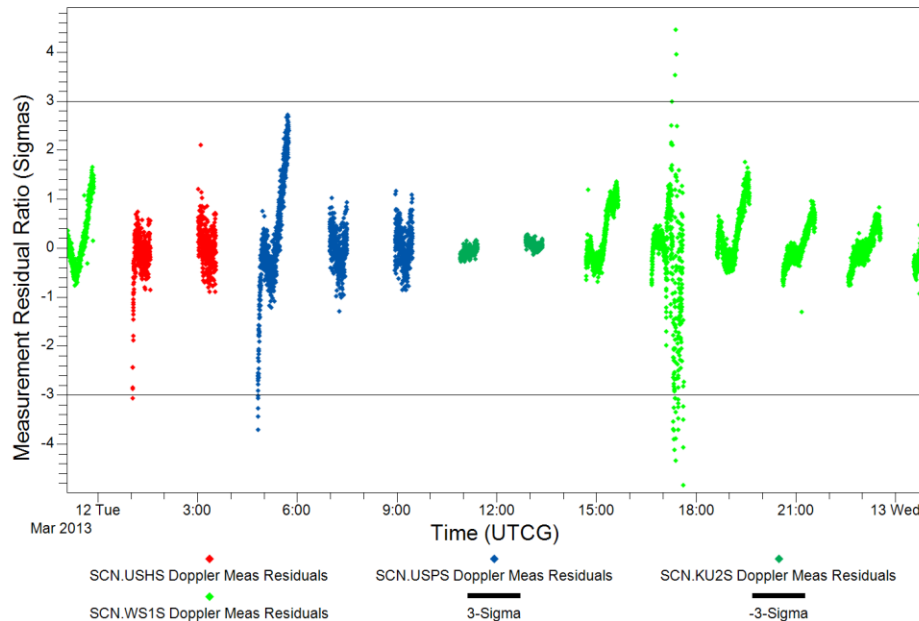
Vasicek Estimation



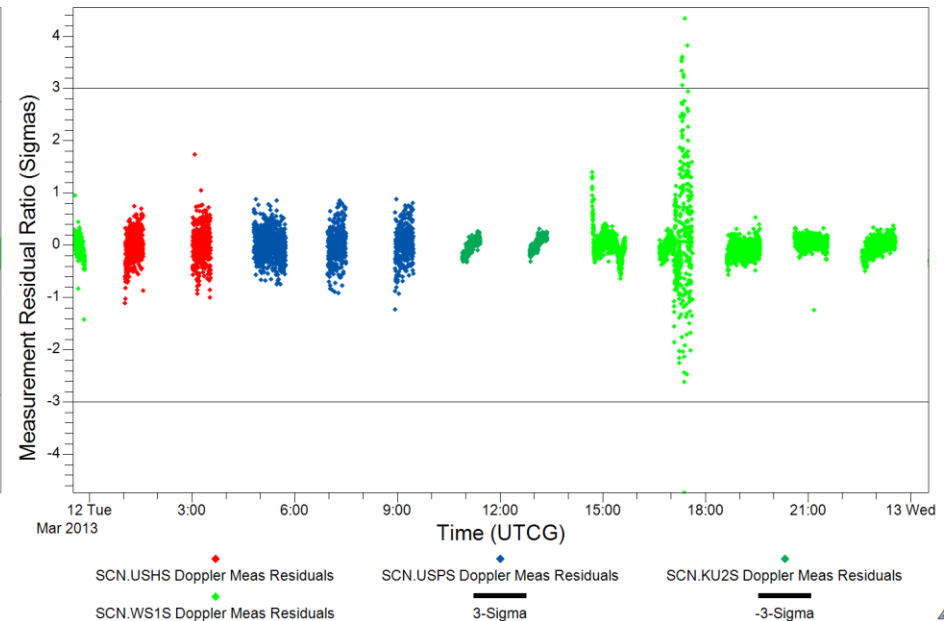
- ***The estimate of the correction from the Gauss-Markov model has more noise than the Vasicek estimate***
- ***The Vasicek model converges to a value consistent with that estimated by the LOLA precision OD team.***
 - A nominal value of 0.96 was adopted based on the Vasicek estimate

- ***A nominal white noise level of 1 mm/sec was chosen***
 - Examination of residuals showed that 5 mm/sec was more appropriate for the Kiruna stations
- ***All LRO USN trackers are observed to have an approximate range-rate bias of -1 cm/sec***
 - The WS1S station bias is close to zero
- ***Simply applying the nominal biases proved more beneficial than attempting to estimate them***
 - LRO OD is sensitive to the range-rate data, and estimating the bias tends to dilute its effectiveness for the position and velocity update
- ***Modeling the effect of the motion of the high gain antenna (HGA) relative to the center-of-mass (CM) was important***
 - Every range-rate pass has a residual signature from just the orbital motion because of the HGA CM offset
 - Additional large attitude slews occur from time to time
- ***Range-rate residuals are considerably improved when the spacecraft attitude and HGA offset are taken into effect***
 - Filter-smoother consistency was also dramatically improved

Without HGA Motion Modeling

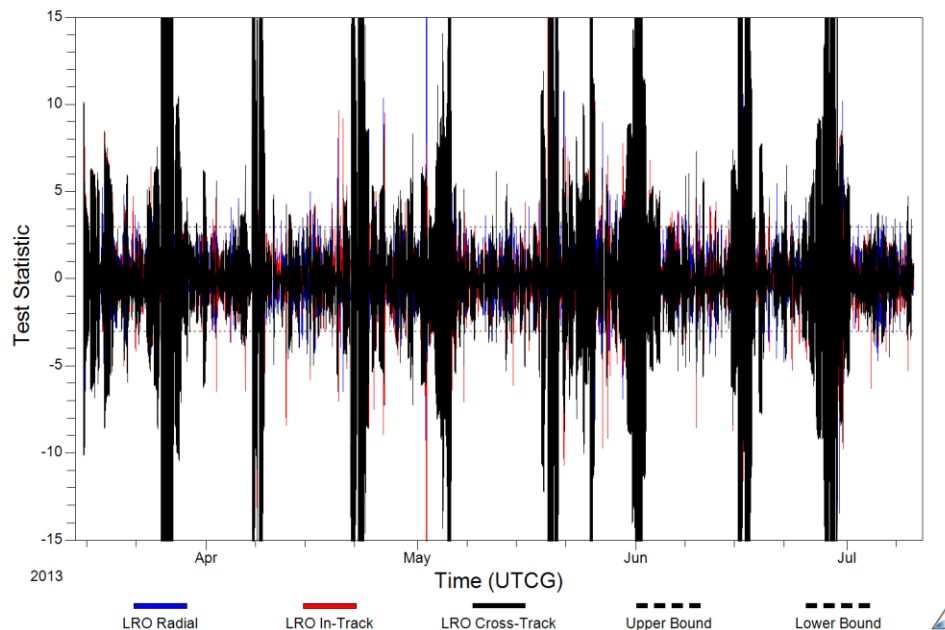


With HGA Motion Modeling

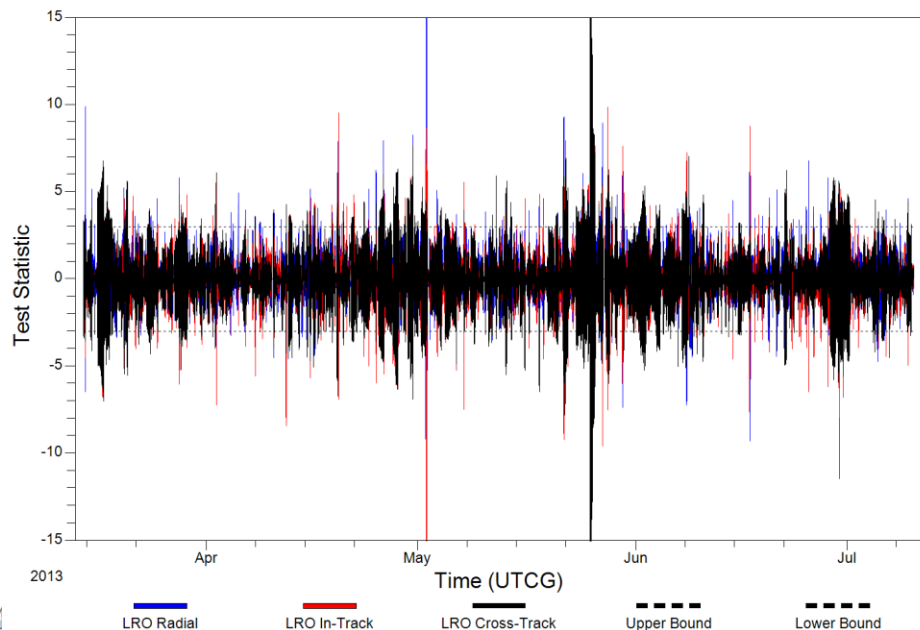


- ***Residuals are much closer to “white noise”***
- ***Some excessive residual noise is still evident during spacecraft slews, even when using definitive attitude history data***

Without HGA Motion Modeling



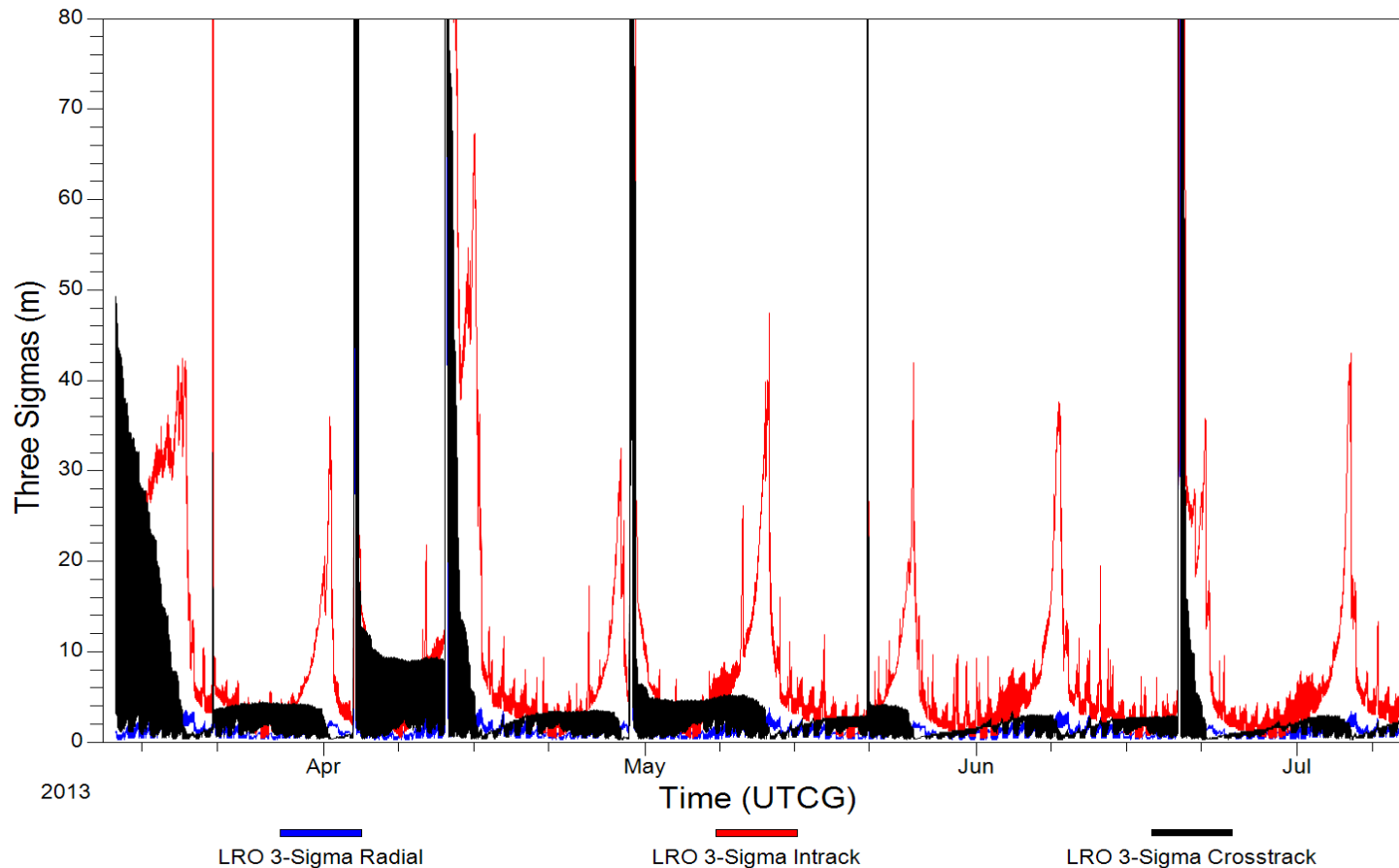
With HGA Motion Modeling



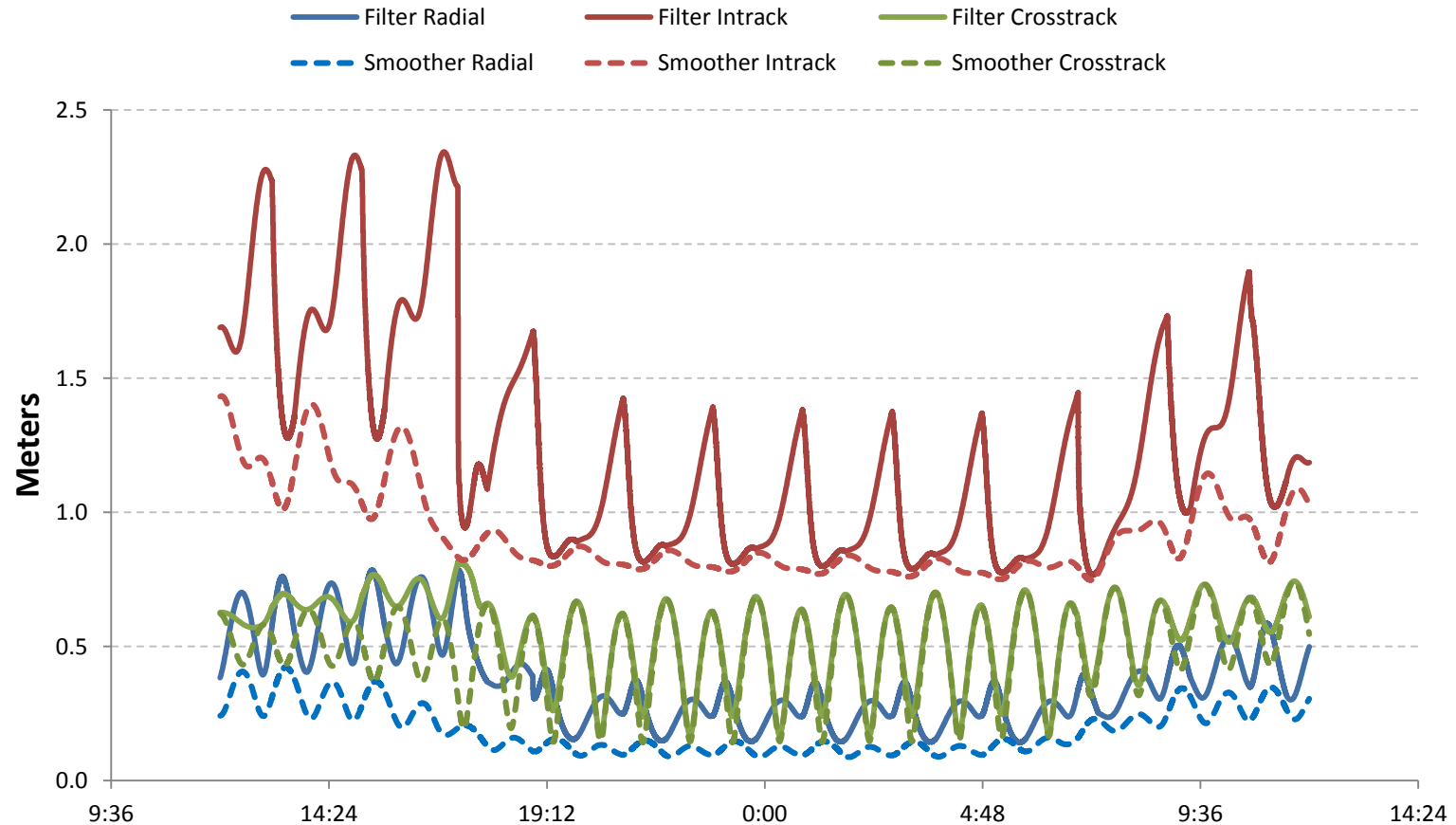
- ***Filter-smoother consistency is much better with HGA motion modeling***
- ***The definitive and predictive accuracy metrics for these cases are very similar, but consistency for the HGA modeling case is dramatically better***

- ***OD accuracy requirements can be met using range-rate data only***
- ***LRO's range tracking has some anomalies that must be addressed***
 - Various calibration biases on the order of 10 meters
 - Time tag biases of about +6 msec (WS1S) and -2 msec (USN)
- ***In addition, the introduction of range data forces the analyst to address modeling of the spacecraft transponder delay and range tropospheric delay***
 - With only a single spacecraft in the filter, the transponder delay, range calibration bias, and tropospheric delay are highly correlated
- ***The best solution incorporating both range and range-rate tracking was one that applied the transponder delay and troposphere biases, estimated range biases on each station, and estimated range time-tag biases on each station***

- ***The addition of supplemental generalized process noise improved prediction accuracy and filter-smoother consistency***
 - A value of 1.4×10^{-10} km/sec² was used
- ***Runs that used a spherical area model but did not use some additional process noise (either in the form of supplemental SRP process noise or generalized process noise) diverged***
- ***This magnitude of noise is on the order of the SRP force for a low lunar orbiter***



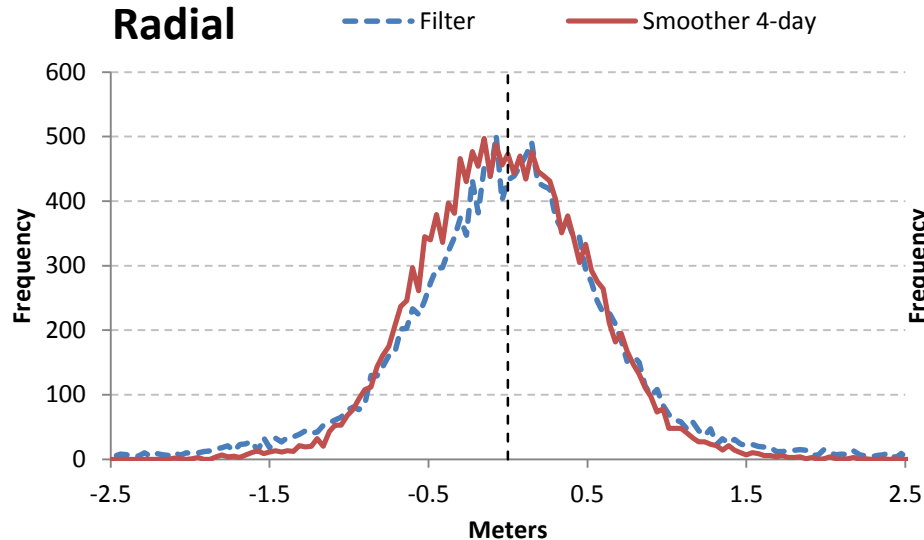
- ***Three-sigma position uncertainty ranges from about 5 to 50 meters***
 - There are large short-term spikes around maneuvers from the coarse modeling employed
- ***In-track uncertainty peaks sharply when the orbit is face-on to Earth***



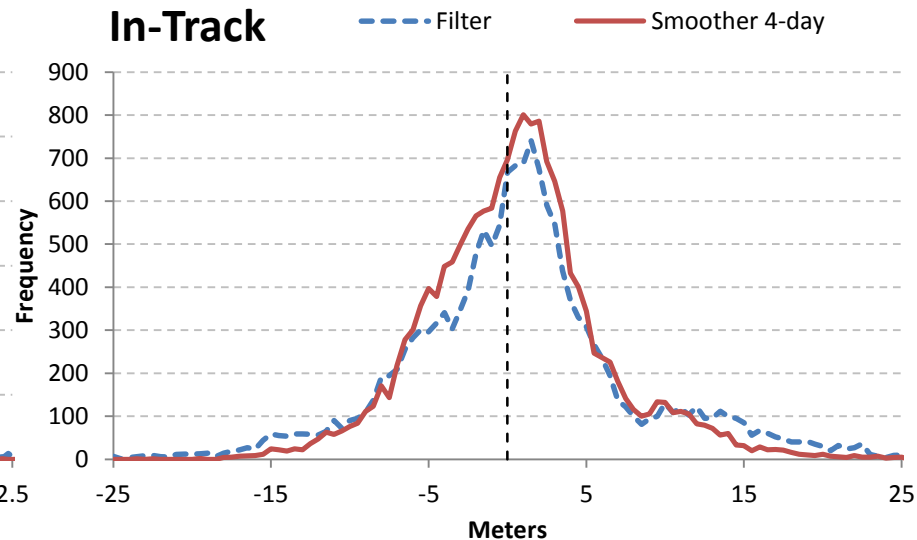
- ***The chart displays a sample comparison span of the filter and smoother covariance***
- ***The largest smoother improvement is in-track***

ODTK Filter and Smoother Difference with Precision Orbit Ephemeris

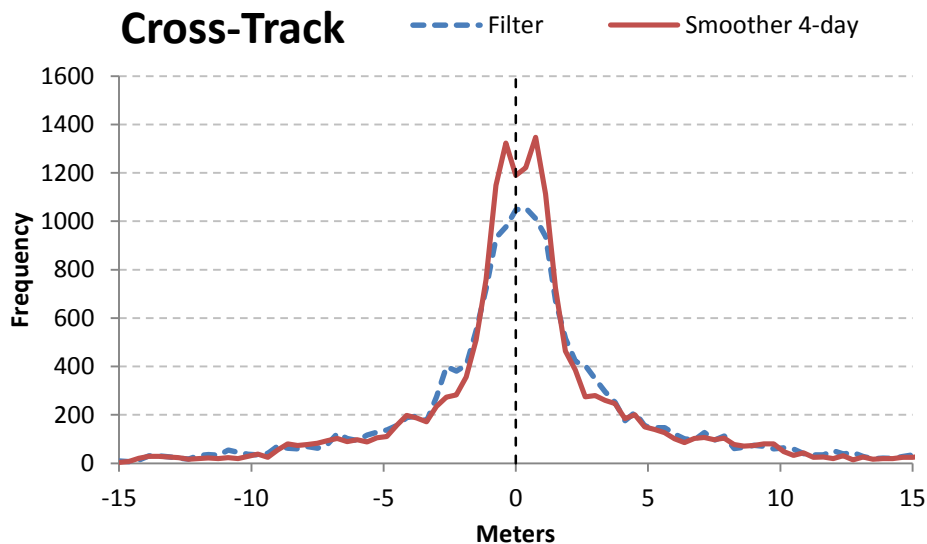
Radial



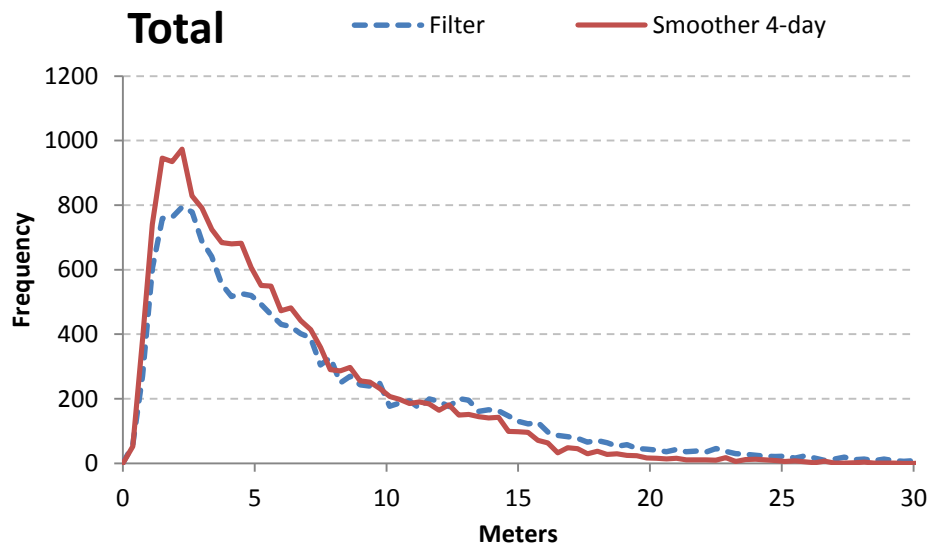
In-Track



Cross-Track



Total



- ***Accuracy was assessed using the LOLA precision OD from GEODYN as the “truth”***
- ***Gross filter in-track performance is worse than GTDS because of filter reconvergence after momentum unloads and maneuvers***

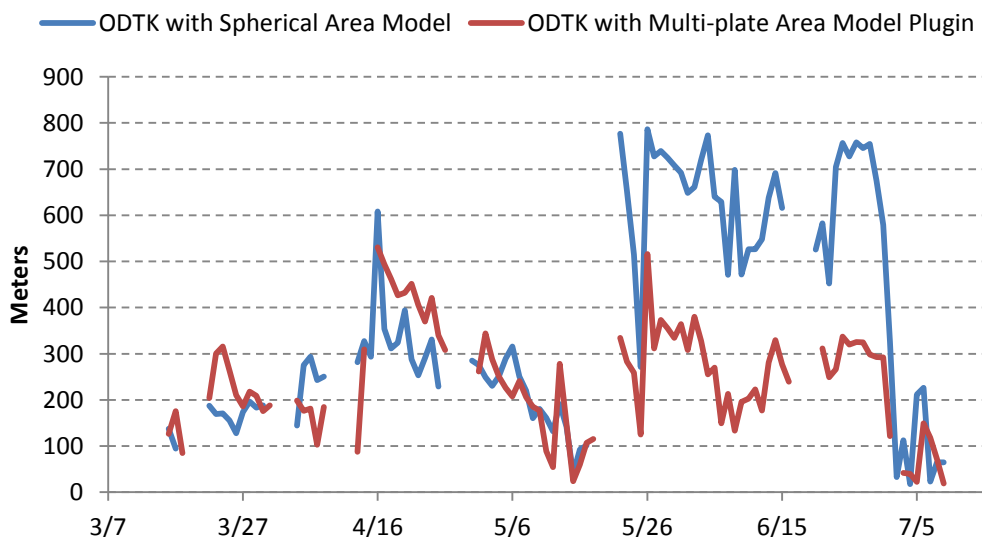
99th Percentile of Definitive Ephemeris Differences
Between ODTK, GTDS, and GEODYN

	Radial (Meters)	In-track (Meters)	Cross-track (Meters)	Total Position (Meters)
GTDS	6	44	77	129
ODTK Filter	2	83	18	106
ODTK Smoother	1	15	14	20

- ***The GEODYN ephemeris is stated as having an RMS radial accuracy of <1 meter and an RMS total accuracy of ~10 meters***

- ***Results shown to this point all used a spherical spacecraft area model for SRP***
- ***ODTK provides the user with plugin points for extending or overriding the native force model computations***
- ***For this analysis, an example SRP plugin provided with ODTK was modified to compute an SRP force based on a multi-plate “box-and-wing” area model***
 - This model includes the spacecraft body panels and the solar array
 - The HGA (about 1 m²) is neglected
- ***Because of power and thermal constraints, the solar array pointing and management depends on beta angle***
 - Low beta angle: the solar array tracks the Sun with a bias to the Sun direction
 - Moderate and high beta angle: the solar array is parked at a particular angle
- ***The various modes of solar array management were modeled by use of multiple versions of the spacecraft area plate file***
 - Each version was swapped in at the appropriate time

	Mean 84-hour Predictive Accuracy (Meters)	Predictive Accuracy Requirement Failures
GTDS with a spherical area model	325	8
ODTK with a spherical area model	381	0
ODTK with a multi-plate dynamic area model	243	0



- ***For both the spherical and multi-plate model, ODTK meets the predicted accuracy requirement throughout the analysis span***
- ***The ODTK spherical model likely outdoes the GTDS spherical model because of ODTK's ability to estimate SRP corrections***
- ***Largest improvements for the multi-plate model are during the high-beta/full-Sun period of May 21 through July 2***

- ***The ODTK EKF met all LRO accuracy requirements over the evaluation span***
 - Definitive accuracy was better than that achieved by GTDS
 - Predicted accuracy did not exceed 800 meters in 84 hours
- ***The best tuning used range-rate data only, and applied appropriate range-rate biases and troposphere corrections***
- ***Inclusion of supplemental process noise was required***
 - With a spherical spacecraft area model, generalized and supplemental SRP process noise was needed
 - With a multi-plate area model, no supplemental SRP process noise was needed
- ***ODTK, with an appropriate stochastic model, enabled SRP estimation, which was not possible with GTDS***
 - The Vasicek model was superior to Gauss-Markov for SRP estimation
 - This improved predicted accuracy when using a spherical area model
- ***Filter-smoother consistency is a sensitive metric for evaluation of force model tuning***
 - HGA motion modeling, not available in GTDS, is critical to achieving good filter-smoother consistency
- ***Use of an EKF has other advantages for lunar OD***
 - The filter and smoother provide a time-dependent covariance
 - Processing time for estimation, prediction, and smoothing is about half that required for GTDS